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LCA OF WASTE MANAGEMENT SYSTEMS

EASEWASTE—life cycle modeling capabilities for waste management technologies

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Abstract
Background, aim, and scope The management of municipal solid waste and the associated environmental impacts are subject of growing attention in industrialized countries. European Union has recently strongly emphasized the role of LCA in its waste and resource strategies. The development of sustainable solid waste management systems applying a life cycle perspective requires readily understandable tools for modeling the life cycle impacts of waste management systems. The aim of the paper is to demonstrate the structure, functionalities, and LCA modeling capabilities of the PC-based life cycle-oriented waste management model EASEWASTE, developed at the Technical University of Denmark specifically to meet the needs of the waste system developer with the objective to evaluate the environmental performance of the various elements of existing or proposed solid waste management systems.
Materials and methods The EASEWASTE model supports a full life cycle assessment of any user-defined residential, bulky, or garden waste management system. The model focuses on the major components of the waste and reviews each component in terms of the available waste management options, including biogasification and composting, thermal treatment, use on land, material sorting and recycling, bottom and fly ash handling, material and energy utilization, and landfilling. In order to allow the use of the model in an early stage where local data may be limited, default data sets are provided for waste composition and quantities as well as for the waste technologies mentioned above. The model calculates environmental impacts and resource consumptions and allows the user to trace all impacts to their source in a waste treatment processes or in a specific waste material fraction. In addition to the traditional impact indicators, EASEWASTE incorporates impact categories on stored ecotoxicity, specifically developed for representation of the long-term impacts of persistent pollutants in landfilled waste. The model reports data at any stage of the LCA and supports identification of most sensitive parameters as well as overall sensitivity analysis and material balances for all substances passing through the system.
Results and discussion The structure of the model is presented, and its functionalities are demonstrated on a hypothetical case study based on waste data from a large Danish municipality. The aim of the case is to demonstrate new waste treatment technologies and their modeling capabilities as well as the LCA modeling capabilities in EASEWASTE to identify the most important impact categories and the main sources of contributions to these in the system for treating the waste. Based on the results, the modeling features, user flexibility, and transparency of the EASEWASTE model are discussed.
Conclusions EASEWASTE is demonstrated to be a versatile and detailed (engineering) model with a strong differentiation of individual fractions, but it requires an engineering background to use all the features. The model is especially developed for the modeling of the handling of municipal solid wastes, and therefore, it does not support other wastes such as demolition and large commercial

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waste. The model is useful for an iterative approach to waste system modeling; its database access supports a quick primary calculation of the impacts from a designed waste system using default data, and based on this, a gradually refined focusing on the parts which contribute the most to the total impacts. The EASEWASTE model allows the user to supply detailed data for waste generation, waste composition including material fractions and chemical properties, sorting efficiencies, waste collection, and waste treatment technologies. More generic LCA modeling tools developed for LCA of products do not support these steps of the modeling to the same extent, and also the creation and evaluation of waste collection, waste transportation, and waste treatment technology individually or in a designed scenario is much easier in EASEWASTE.

Recommendation and perspectives EASEWASTE has been used in the modeling of a number of real case studies, and much data have been incorporated into it. Several research projects are currently underway under the Danish 3R (Residual Resources Recovery) research school in support of its further development. There are, however, still many issues that have to be improved significantly to facilitate application by other users than model developers. The improvements in consideration are to provide data for more treatment and disposal technologies and more flexibility. The current version of the model supports the environmental assessment (environmental impacts and resource consumption) of household and small commercial business units waste treatment systems in a Danish context, but it is the ambition that future versions of the model shall support the inclusion of other waste types as well as economic evaluation and that the geographical coverage shall be extended to other countries.

Keywords EASEWASTE model · Environmental assessment · Life cycle assessment · Material flow analysis · Sensitivity analysis · System modeling · Waste management system · Waste planning

1 Introduction

The management of municipal solid waste and the environmental impacts it causes are subject of growing attention in industrialized countries. The United Nations General Assembly has pointed out environmentally sound management of wastes as being of major concern in maintaining the quality of the Earth's environment and in achieving environmentally sound and sustainable development (Agenda 21 1992). European Union (EU) has recently strongly emphasized the role of life cycle assessment (LCA) in its waste strategy, where a life cycle perspective shall now be applied in the optimization of the management of waste (EU 2005).

1.1 Life cycle modeling of waste management systems

The development of sustainable solid waste management systems applying a life cycle perspective requires readily applicable tools for modeling the life cycle impacts of the systems (Den Boer et al. 2005a). EASEWASTE helps overcome the practical problems of modeling a complex system by supporting the user's construction of a model of the waste system's life cycle and providing data for many of the processes which are involved (Kirkeby et al. 2006a, b; Christensen et al. 2007). The resulting model is a simplified (aggregated) representation of the integrated waste management system. The EASEWASTE model is a deterministic model formulated using mathematical equations. It is constructed from individual elements describing the unit processes of the waste management system, like waste collection by truck or an incineration technology and the quantitative relations between these elements.

The processes which are involved in a waste management system have their very different nature and own specifics which need to be considered. For each process or family of processes, a parameterized module has been established in EASEWASTE. The definition of the parameterized models involves determination of transfer coefficients, often obtained by experiments which describe the flows through the process, quantifying the outputs of the process for varying inputs. Furthermore, some parametric process modules require mathematical and logical equations to transfer chemical input parameters characterizing the waste composition into relevant emissions. Due to the large number of different inputs and outputs needed for the LCA of a waste management process, this is quite an expensive approach, but there is no other way to support the required level of sophistication than to collect this kind of data. Most of these modules have been published and discussed in some detail in earlier papers (Hansen et al. 2006; Kirkeby et al. 2006a, b, 2007; Riber et al. 2008; Manfredi et al. 2009a, b; Zhao et al. 2009; Niskanen et al. 2009). The focus of this paper is to demonstrate the EASEWASTE model in full including its structure, functionalities, and integrated LCA modeling capabilities.

1.2 Existing tools for life cycle assessment of waste management

Basic capabilities for environmental assessment of solid waste management systems are already available in general LCA models, and these have also been used for evaluation of waste management (Johnsen et al. 2002). However, it should be noted that while LCA was developed for environmental assessment of products, the life cycle boundaries of product systems and waste management systems are fundamentally different. The life cycle of a

waste system starts when a material is discarded into the waste stream and ends when the waste material has either been converted into a resource (such as recycled material or recovered energy), or when it has finally become a part of the ecosphere (Hauschild and Barlaz 2009). Being developed to support product development and modeling of product life cycles, applying a systems perspective, existing product LCA tools may also be applied in modeling of waste management systems, but it is typically quite a time-consuming process. These models do not support the parameterized waste treatment models which are needed to calculate waste-specific emissions using transfer coefficients for the different waste treatment technologies, and they do not support the application of a user-defined waste composition, used defined sorting fractions, sorting efficiencies, and transfer coefficients for each of the defined chemical composition groups of the waste. Furthermore, the databases of product LCA tools do not comprise many of the specific waste treatment processes, and if they do, it is rarely in the parameterized form which allows adaptation to the specific system which is studied. Therefore, tools have been developed specifically for assessment of waste management models over the years. Some of the more prominent are EPIC/CSR, Canada (EPIC 2004); ISWM-DST, USA (Solano et al. 2002a, b; Kaplan 2004; Weitz et al. 1999); IWM2, UK (Procter & Gamble 2005); LCA-IWM, EU (Den Boer et al. 2005a, b); ORWARE, Sweden (Dalemo et al. 1997); WISARD, UK (Ecobilan 1999 and Ecobalance 2009); Waste Analysis Software Tool for Environmental Decisions (WASTED; Diaz and Warith 2006); Waste Reduction Model (WARM; US EPA 2006); and WRATE (UK Environment Agency 2007). The performances of these models have been compared and reviewed in RTI (2006). They support a full LCA in very varying degrees. Some models are thus limited to calculating the inventory of the system's environmental exchanges while other models support the further evaluation phases of the life cycle assessment in a limited fashion only.

1.3 Why software specifically designed for waste management systems?

The combinatorial nature (many waste items and fractions of the treated waste flow and many management options and individual technologies) and multiple objectives of the solid waste management lead to proposal of several optimization-based research procedures by the researchers. These procedures, however, enjoy limited use due to the substantial expertise required for their application. There is no single right way provided to manage municipal wastes responsibly. One community running out of landfill space is making a major investment in recycling. Another is investigating energy recovery options, and a third has made a serious commitment to expanded composting programs. Each hopes to adopt a practical, affordable, and environmentally sound treatment alternative to solve their local waste disposal problems. Life cycle thinking in waste management planning and policy is also emphasized by the European Union Strategy for Sustainable Consumption and Production. There is hence a growing need and interest to integrate LCA in the development and optimization of waste management systems. The EASEWASTE, a life cycle-oriented advanced engineering tool for waste management, has been developed to model the environmental impacts from solid waste management systems combining numerous technologies with a high degree of flexibility.

2 The EASEWASTE model

EASEWASTE is a PC-based gate-to-grave life cycle-oriented waste management model especially designed to meet the needs of the waste system designer and including all processes in the waste management systems as well as upstream and downstream of the waste management systems. The EASEWASTE model is an engineering model with a high differentiation in the modeling of the individual components of the different waste fractions. It provides a full flexibility to modify or redefine data at any level (waste collection, transportation, treatment, recovery, and disposal) in a scenario. The changes can be made at any level of modeling inside a scenario modifying the supplied default data. The model allows the user to create new waste treatment technologies for different types of waste treatment to supplement the modules provided in the database of the model. Material balances can be calculated for any individual element of the waste system model as well as for the entire scenario.

The EASEWASTE model supports the environmental assessment of waste management of an amount of household waste generated in an area that is divided into three main types of residential areas: single-family housing, multifamily housing, and small commercial business units (SCBU) producing household-type waste. The model calculates environmental impacts and resource consumptions for any user-defined waste treatment system as well as any individual technology or process and allows the user to track them to their source in a waste treatment process or to a specific waste material fraction. The model supports system expansion to calculate the impacts from recycling/reuse of materials and the associated savings in environmental emissions and resource consumption as credits to the waste management system. Sensitivity analysis can be performed on any selected process/material/fraction/type (e.g., single-family housing). Model also supports to calculate sensitivity ratio which helps the user to rank the individual materials and processes according to their contribution to the total impacts.

2.1 Functional unit

The model operates on a functional unit which is a given amount of solid waste of a specified composition generated for an area.

2.2 Boundaries and limitations

The model boundaries cover bin-to-grave, i.e., from the point where products become waste and put into the waste bin at the waste generation source to the point where the waste either has been converted into a useful material (recycled materials including reuse in agriculture) or has become part of the environment after final disposal as illustrated by the shaded area in Fig. 1. The EASEWASTE model consists of a number of modules (waste treatment technologies) grouped into the following: sorting of materials (organic/nonorganic) at a materials recovery facility (MRF), recycling of materials, biotreatment (composting and anaerobic digestion), use-on-land (UOL), thermal treatment, mineral waste landfill, mixed waste landfill, material utilization, energy utilization, Air Pollution Control (APC) treatment, and bottom ash treatment.

In the development of the EASEWASTE model, a number of limitations have been introduced:

- The model has been mainly developed for waste types from households and small commercial business units and does not address the management of other waste streams such as demolition and construction waste.
- To support modeling of the complexity of the waste management system, the model operates with 65 material fractions, each fraction with 45 characteristics such as substances, lower heating value, and methane potential. The names of the material fractions and substances can easily be modified as the user desires.
- The model allows definition of up to ten sorting fractions with separate sorting efficiencies for collection of waste at each waste generation source (single-family, multifamily, and SCBU) in a scenario.
- External activities which are used as background processes in the modeling of the waste management system (for example fertilizer production) are described in the database as one level terminated processes rather than process systems in order to avoid eternal loops in the program, leading to instability.

2.3 Structure

The EASEWASTE model has been structured so that it can use data specific to an actual case thereby improving the accuracy and applicability required. At the same time, in order to allow the use of the model at an early stage where local data may be limited, default data are provided. Figure 1 illustrates the structure. The user experiences an

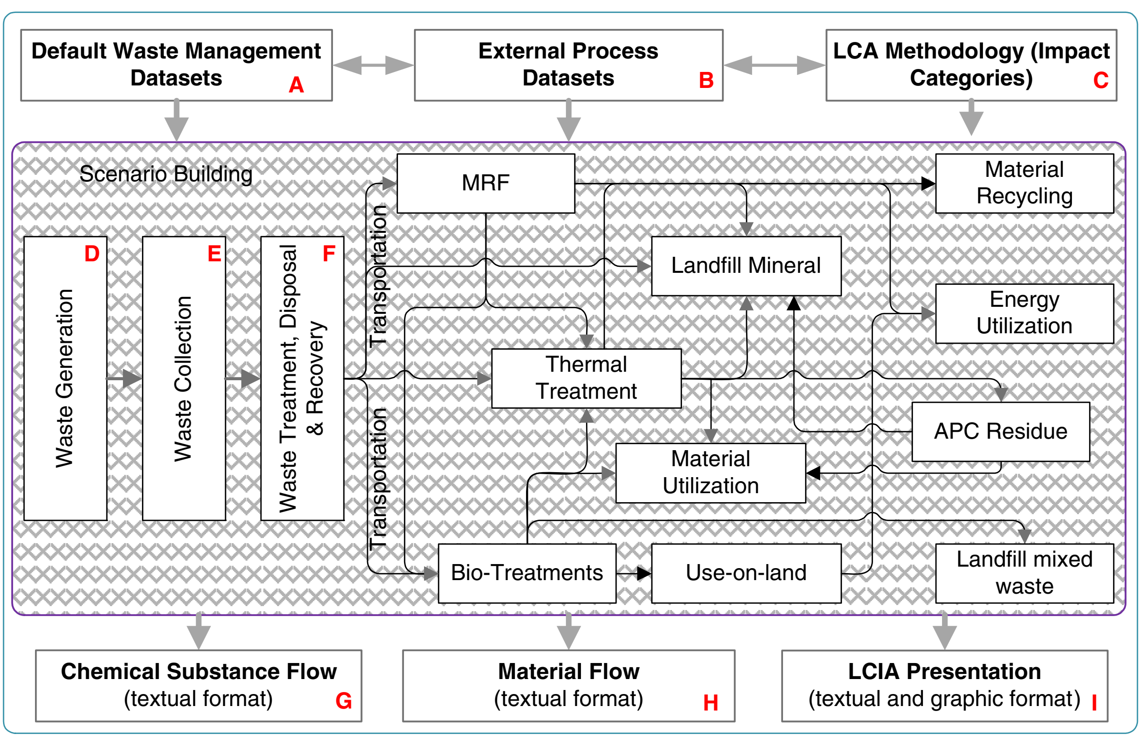


Fig. 1 Structure of the EASEWASTE model

input interface comprising (A), (B), (C), (D), (E), and (F) and an outputs interface (G), (H), and (I). The input interface addresses definition of the waste management system (A), (D), (E), and (F), and the life cycle impact assessment (C). Interface (A) allows the user to create waste compositions, quantities, sorting efficiencies, collection, transportation, and waste treatment technologies datasets (default datasets). Interface (B) allows the user to create/modify flows (substances) for the different emission compartments (e.g., resources, air emissions, groundwater emissions, freshwater emissions, marine water emissions, soil emissions, solid emissions, stored soil emissions, and stored water emissions compartments, etc.) and to create or modify external process datasets, e.g., electricity production, general transportation or iron scraps material dataset. Interface (C) allows the user to create environmental impact assessment categories (e.g., global warming, acidification, ozone depletion, etc.) and to define impact assessment methods (in addition to EDIP 1997 and 2003, which are already supported by the tool).

A waste management scenario (D, E, and F) consists of three consecutive components modeling, respectively, waste generation, waste collection, and waste treatment/recycling/disposal. Each of these components is defined for three waste generation sources: single-family housing, multifamily housing, and small commercial business units, allowing differentiation of the waste management system for different types of areas. Definition of the waste generation component includes quantifying waste material fractions and the chemical and physical properties of each material fraction. The waste collection component includes a system for source-separation, collection, and transportation of collection fractions. The waste treatment recovery and disposal component includes different treatment options (processes) and a number of technologies within each chosen treatment option for each collection fraction and any subsequent treatment of any residuals from prior treatment. Each treatment process (module) treats the primary waste and produces a secondary waste or recyclable products and emissions to environment. The primary waste is the waste entering a treatment process from a waste source, while secondary waste is generated in a treatment process (the solid outputs from the process). For example, source-separated organic waste is a primary waste, while incineration slag and fly ash are secondary wastes. Each module calculates the turnover of materials, the use and production of energy, as well as generation of process specific emissions, and it provides the outputs for each module individually. Material turnover is characterized by the supply of waste materials and process chemicals, and by the output of products (recyclable materials), secondary wastes, and emissions to air, water, and soil. Energy turnover is the use of different energy carriers such as coal and oil, and the production and recovery of, e.g., heat, electricity, or biogas.

EASEWASTE allows for easy changes in the technologies used in a scenario by sampling modules from the default list of technologies or by adjusting within the scenario individual parameters characteristic of a technology.

The model provides a presentation (G) of the input and output of all chemical or physical characteristic elements for each module as well as for the system at the wanted level of aggregation. Presentation (H) provides the user with the possibility to view primary and secondary waste amount through each module. Output window (I) provides a detailed presentation of life cycle inventory, impact potentials in characterized, normalized, and weighted form in textual and graphical formats. The presentation part of the model also supports identification of the main contributions to each category at the level of a module/material/process or a single input substance.

3 Case study

The case study is provided to demonstrate the modules' usability, model functionalities, and life cycle-oriented modeling capabilities as well as flexibility, validity, and user friendliness of the EASEWASTE model in handling complex waste management systems.

3.1 Description of case study

A scenario, demonstrated in Fig. 2, is deliberated with real data from a typical large city of Denmark. Approximately 150,000 inhabitants reside in single-family houses in this city. They generate approximately 44,000 t of waste per year (single-family housing). The waste generation is defined by the number of dwellings, persons per dwelling, and a specific unit waste generation rate per person per year (Petersen and Domela 2003). The single-family, multifamily, and small commercial waste generation sources can be modeled individually or all in a single scenario. Assumptions underlying the calculation of waste generation from single-family housing are seen in Table 1.

As illustrated in Fig. 2, the household waste is collected from curbside and further sort-separated into three main sorting fractions: organic waste (10,179 t), mixed papers and cardboard (7,469 t), and residual waste (25,464 t). Organic waste is routed to the bio-treatment (anaerobic & aerobic process) plant for methane gas collection, treatment, and energy recovery. The secondary waste outputs (*compost and residue*) from biotreatment are further routed to use-on-land for use as fertilizer and to landfill (mixed waste).

The paper and cardboard fraction is routed to a MRF. Secondary outputs from the MRF (*paper and residue*) are

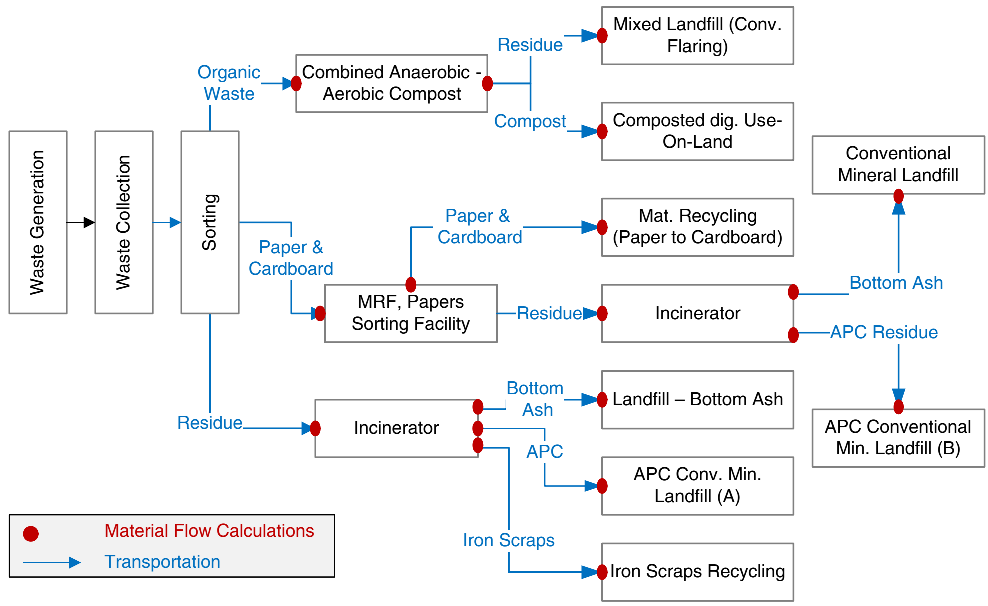


Fig. 2 Structure of the modeled waste management scenario

further routed to material recycling technology to manufacture cardboard and to thermal treatment for incineration. The secondary outputs (*APC residue and bottom ash*) from thermal treatment are assumed to be landfilled in conventional mineral landfills separately.

The residue fraction from the sort-separation is assumed to be incinerated using an appropriate thermal treatment technology. Secondary outputs from thermal treatment (*bottom and fly ash, and iron scraps*) are assumed to be recycled and landfilled in conventional landfills separately.

All transportation for collection of waste from curbside and transportation of secondary materials from one treatment option to another option are also included.

4 Results

In the following, the EASEWASTE model is presented and its modeling capabilities and functionalities are demonstrated, applying results for a typical large municipality of Denmark. The aim of this hypothetical case is to present the capabilities and functionalities available in the EASEWASTE 2008 model and guide the waste planner to track the most significant processes/technologies/materials/substances from any user defined waste system.

Results from the case are described with the aim of illustrating the different functionalities and types of outputs obtained from the EASEWASTE model. The results for the balance checks, inventory, impact assessment, and material and sensitivity analysis are shown separately, and the features, user flexibility, and transparency of the EASEWASTE model are discussed. The actual results are shown only for illustrative purposes.

4.1 Inventory

The inventory quantifies the resources and emissions from all processes, or if wanted for all individual material flows or waste composition fractions in a waste management system, defined in accordance with the scope definition, and presents the information in a transparent form at the desired level of aggregation per process, material, sorted fraction or waste generation source (single family, multi-family, or SCBU). Figure 3 shows the aggregated results from the first level of the life cycle inventory of single-family waste generation source with total and the three defined stages in waste generation source (waste collection, transportation, and treatment disposal and recovery) separately. The model provides short cut functions to calculate inventory on different levels of aggregation from single waste generation source (single family, multifamily, or SCBU) or single sorting fraction (e.g., paper and cardboard and organic waste) over single selected treatment process or material to life cycle stage or the full system. These functions help the user to identify and track the most significant contributors to the environmental impact potentials in the waste or in the treatment system at the desired level of detail.

Table 1 Waste generation data from single-family houses (Tønning 2003)

Single-family houses		
Number of houses	58,200	Houses
Persons per house	2.62	Person/house
Yearly waste generation	283	kg/person/year

Substance	Emissions List				HOUSEHOLD WASTE MANAGEMENT SCENARIO - SINGLE FAMILY		
Substance Name	Category	Emission	Unit	Total Amount	Collection	Transportation	Treatment, Recovery and Disposal
Mercury (Hg)	Emission	Air	kg	0.4964	0.0008353	0.001036	0.4945
Zinc (Zn)	Emission	Air	kg	-34.11	0.1311	0.1626	-34.41
Chromium (Cr)	Emission	Air	kg	-1.643	0.008332	0.01034	-1.662
Nickel (Ni)	Emission	Air	kg	-3.584	0.216	0.268	-4.068
Carbon Monoxide (CO)	Emission	Air	kg	1264	645.3	779.2	-160.1
Nitrogen Oxides (NOx)	Emission	Air	kg	-9.298E4	4132	4893	-1.02E5
Particles - PM 10	Emission	Air	kg	215	100.5	114.5	
Sulphur Dioxide (SO2)	Emission	Air	kg	-1.428E5	314.9	390.7	-1.435E5
Lead (Pb)	Emission	Air	kg	-23.8	0.02085	0.02587	-23.85
Selenium (Se)	Emission	Air	kg	-0.1165	0.003984	0.004943	-0.1255
Carbon Dioxide (CO2 - Fossil)	Emission	Air	kg	-2.285E7	4.438E5	5.506E5	-2.385E7

Fig. 3 Excerpts of the life cycle inventory of the modeled waste treatment system

4.2 Impact assessment

Impact characterization translates and aggregates the values in the LCI into environmental impacts and resource consumption scores. In this case, the EDIP1997 impact assessment method (Wenzel et al. 1997) is applied, but any LCIA midpoint or endpoint method can be implemented in EASEWASTE. The impact categories considered here represent a selection of the EDIP97 categories including global warming, 100 years (GW100), acidification (AC), nutrient enrichment (NE), human toxicity via water (HTw), human toxicity via air (HTa), human toxicity via soil (HTs), chronic ecotoxicity in water (ETwc), and ecotoxicity in soil (ETs). In addition, two impact categories are included, which have been developed specifically for the LCIA of solid waste treatment systems: stored ecotoxicity in soil (SETs) and stored ecotoxicity in water (SETw), representing the ecotoxicity potentials of the persistent chemical substances remaining in a landfill after a foreseeable future (100 years) with a potential to cause eco-toxic impacts if/when they are released to the surroundings (Hansen et al. 2004; Hauschild et al. 2008). The resulting environmental impacts may have a negative value indicating that the waste management system in the scenario leads to avoidance of an impact due to displacement of external virgin materials or energy such as electricity or district heating. Figure 4 shows the environmental impact potentials of the modeled scenario. The treatment, recovery, and disposal stage of the scenario is the most significant stage for all environmental impact categories, but there are notable contributions to human toxicity via soil and ecotoxicity in soil for the waste collection stage and the waste transportation stage (internal transportation from one waste treatment technology to another) as well.

4.3 Normalization

Normalization prepares for a comparison across impact categories by relating the different impact scores to a common reference: the impact of an average person in a year (a Person Equivalent (PE)) while still keeping in mind that the difference in severity between the impact categories is not expressed without a formal weighting. Figure 5 shows the contribution to the normalized impact scores from each of the three stages (collection transportation, transportation between treatment options, and treatment, recovery, and disposal). The treatment, recovery, and disposal stage contributes significantly to human toxicity via soil, stored ecotoxicity in water, stored ecotoxicity soil, and human toxicity via water. The scores for acidification, global warming, chronic ecotoxicity in water, and nutrient enrichment are negative indicating that the treatment recovery and disposal stage also leads to avoidance of an impact due to energy production in the thermal treatment and bio-treatment process. The human toxicity impact via soil impact also has strong contributions from the stages waste collection (2,125 PE) and waste transportation (2,544 PE).

The categories human toxicity via soil and stored ecotoxicity via water have the highest normalized scores in all stages. Step-back calculations are performed to track their main contributors (processes, materials, or waste

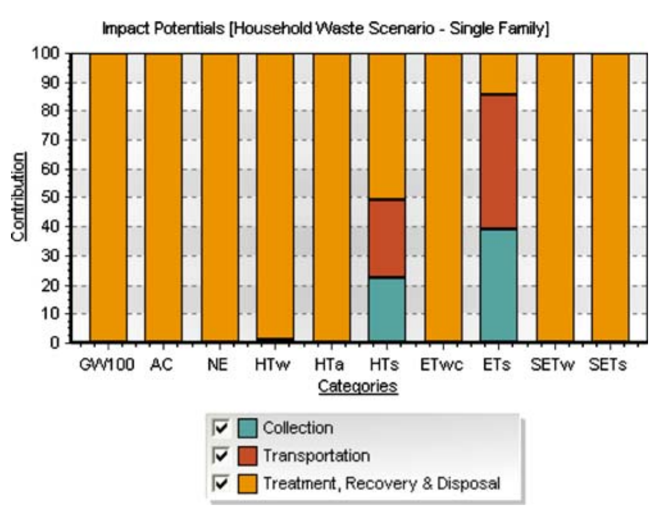


Fig. 4 Characterized impact potential profile of the modeled waste treatment system

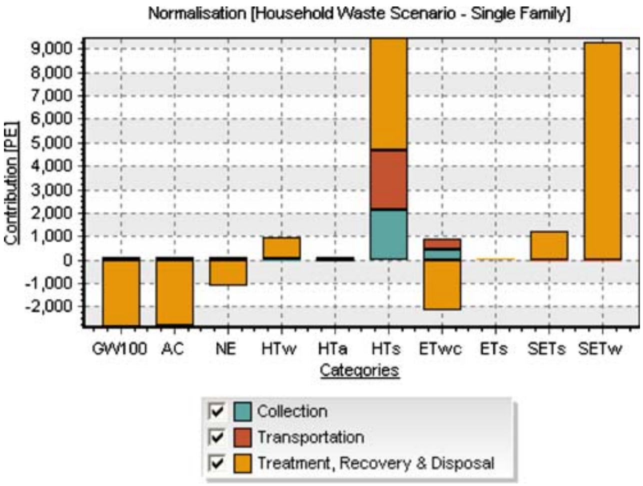


Fig. 5 Normalized impact potentials split into the three stages considered in the modeled scenario

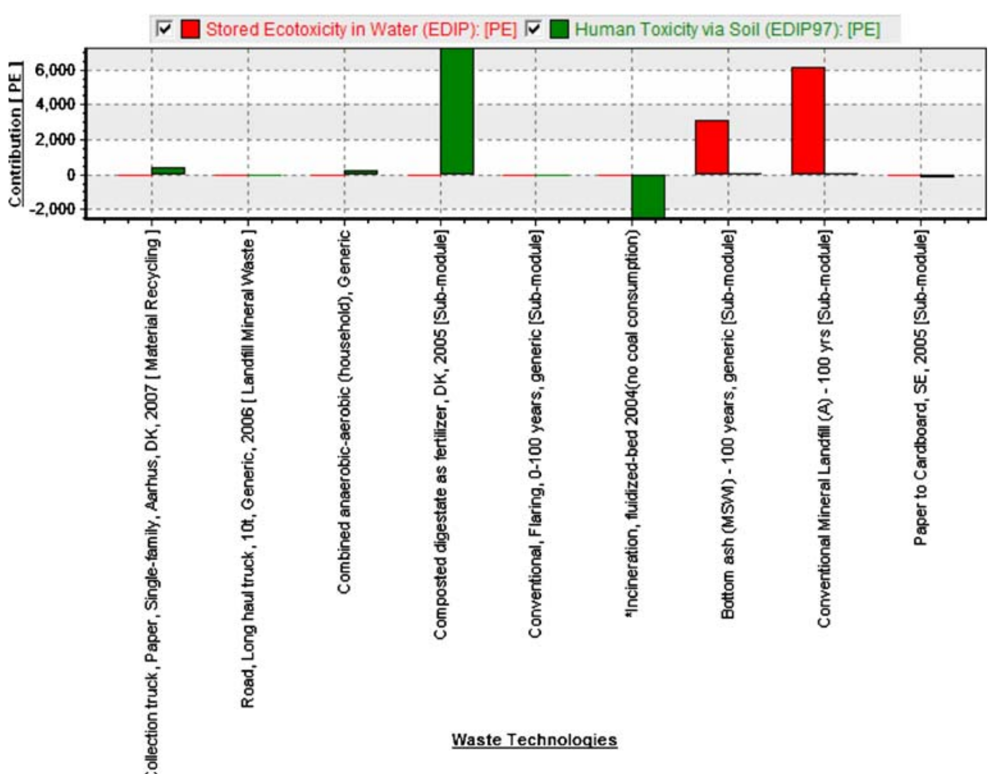
specific chemical substances). Figure 6 demonstrates the contributions to human toxicity via soil and stored ecotoxicity via water from all processes. Use-on-land (composted digest used as fertilizer), collection transportation, and transportation between treatment options are the dominant contributors to human toxicity via soil. Thermal treatment and recycling (paper and cardboard) technologies are contributing negatively indicating that these technologies lead to avoidance of a human toxicity via soil impact due to energy production from the thermal treatment process. Total 25,464 t of waste is routed to thermal treatment, and 10.948 GJ/t energy is generated (calculated based on the lower heating value) which leads to avoidance of contributions to the impact categories global warming, acidification, nutrient enrichment, and human toxicity via soil. Landfills (conventional mineral landfill (A) and bottom ash) are the dominant contributors to the stored ecotoxicity in water.

The main contributing processes can further be investigated as illustrated below for UOL and conventional mineral landfill technologies.

4.3.1 Use-on-land

The secondary output of 1,883 t of compost from the biotreatment technology (biogas and composting) is routed for the use on land as fertilizer (see Fig. 2) which contributes significantly to human toxicity via soil (7,734 PE) through its content of residual pollutants. Figure 7 shows that process specific emissions (emissions created in the foreground system by waste treatment processes) are the main contributors to human toxicity via soil. Process-specific emissions are also considerable contributors to human toxicity via water and nutrient enrichment. The substitution of fertilizer (avoided use due to the soil improving qualities of the compost) leads to avoidance of human toxicity via soil, human toxicity via water, and nutrient enrichment, particularly the substitution of phos-

Fig. 6 Contribution from different waste treatment processes to human toxicity via soil and stored ecotoxicity via water



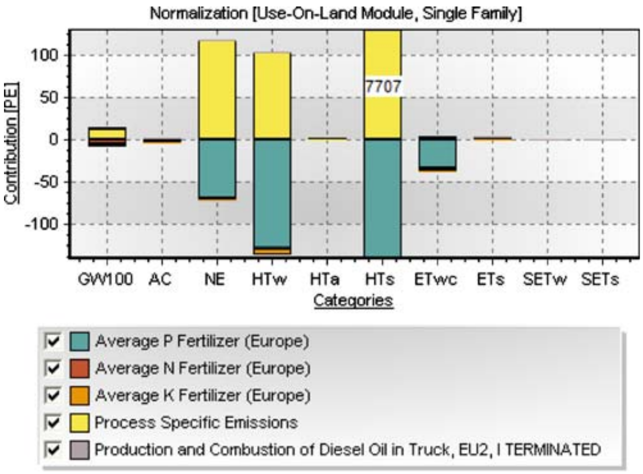


Fig. 7 Contributions of processes/materials/process-specific emissions in the UOL waste treatment technology to the different normalized environmental impact potential score

phate fertilizer, while the transportation work involved in the use on land of the generated compost only shows up in the human toxicity via soil and the chronic aquatic ecotoxicity.

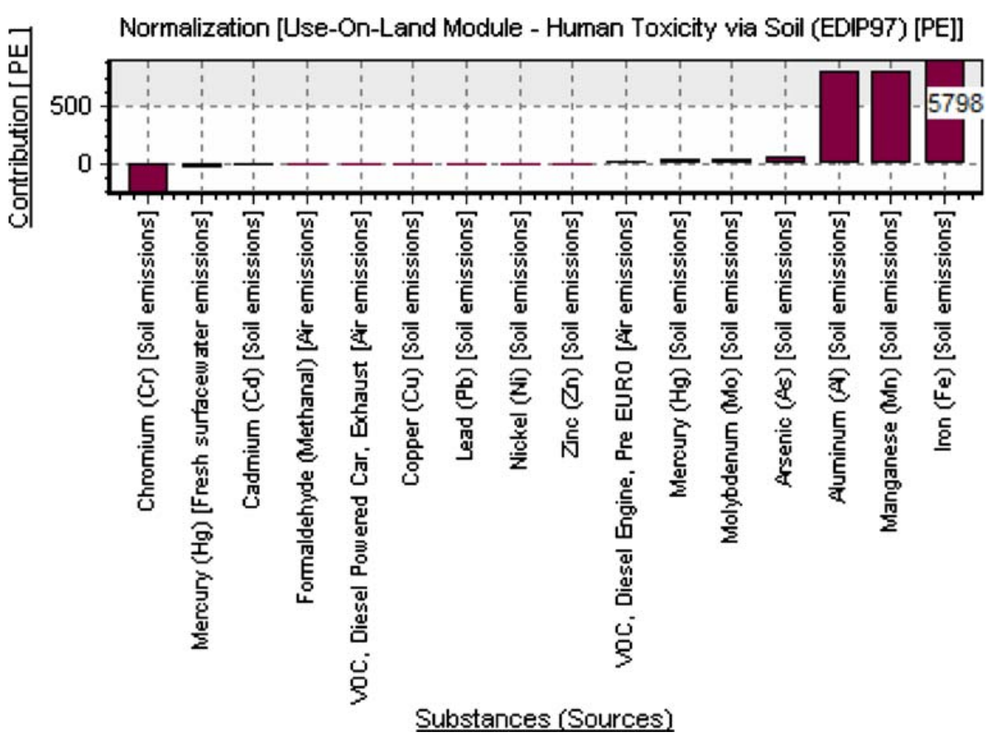
The potential human toxicity via land from the use on land of the generated compost can be further backtracked to identify those substances that contribute most. Figure 8 shows that emissions to soil of iron (5,799 PE), manganese (807 PE), and aluminum (807 PE) caused by the contents of the compost give the main contributions to human toxicity via soil. Soil emissions of arsenic (65 PE), molybdenum (31 PE), and mercury (27 PE) and air emissions of VOC (from diesel engine, 26 PE) also give visible contributions to human toxicity via soil impact potential. The substitution of fertilizer leads to avoided human toxicity impacts from emissions to soil of chromium (−164 PE) and cadmium (−23 PE) and emissions of mercury to surface water (−36 PE).

The backtracking which has been demonstrated here for the system representing the use on land of the compost can be performed at any level from the full life cycle over individual stages to individual processes to help identify the main sources of important impact scores and facilitate sensitivity analysis and error detection.

4.3.2 Conventional mineral landfill

The APC residue (3,886 t), routed from thermal treatment to conventional mineral landfill (A), contributes significantly to stored ecotoxicity in water (6,135 PE) and stored toxicity in soil (1,007 PE). Figure 9 shows that technology emissions (here, substances left in the landfill after the 100-year period) are the main contributors to stored ecotoxicity in water and stored ecotoxicity in soil. Technology emissions are also contributing to chronic aquatic ecotoxicity. In the modeled waste management system, the materials recycling facility is not applied on aggregate recycle metals, and therefore, most of the metals from the waste end up in a landfill where they contribute strongly to these impact categories. The process emissions are backtracked to identify the most important substances for these impact potentials. Figure 10 shows that copper (stored

Fig. 8 Contributions of the substances in the waste stream to the different normalized environmental impact potential scores



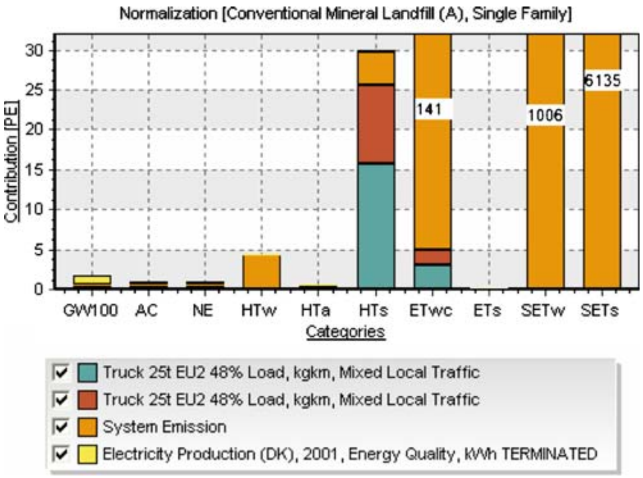


Fig. 9 Contributions of processes/materials/system emission in the landfill technology to different normalized environmental impact potential scores

emissions to water, 5,172 PE), cadmium (stored emissions to water, 599 PE), and lead (stored emissions to water, 287 PE) are the elements in the waste which are the most important contributors to stored ecotoxicity in water. The strongest contributions to stored ecotoxicity in soil are found to come from cadmium (247 PE), mercury (242 PE), and copper (186 PE).

4.4 Weighting

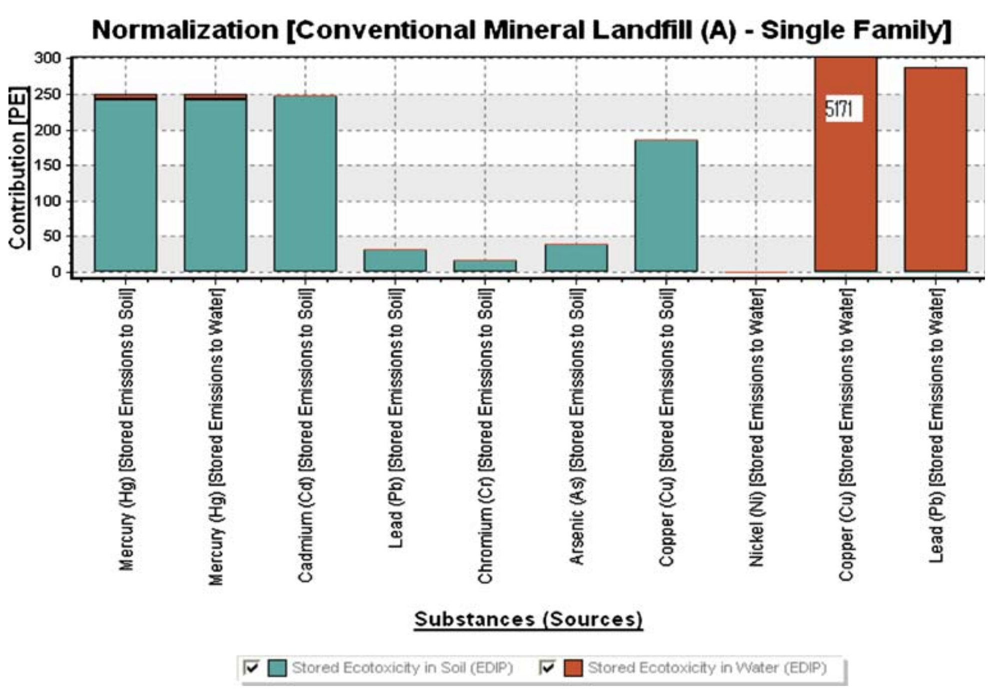
Figure 11 shows the results after weighting with the distance-to-political target-based weighting factors presented as default factors in the EDIP97 methodology (Stranddorf et al. 2005). The weighting now allows a direct comparison across impact categories, and Fig. 11 shows that the treatment, recovery, and disposal stage is a significant contributor to the overall environmental impact potential. This stage also leads significantly to avoidance of acidification, global warming, ecotoxicity water chronic, and nutrient enrichment impacts.

4.5 Sensitivity analysis and sensitivity ratio

The interpretation of the scenario results, whether these are presented as characterized impacts, normalized impacts, or weighted impacts, is facilitated in EASE-WASTE by the possibility of tracking the impacts down to individual technologies, waste sources, material fractions, or individual substances. This feature is very useful when error checking the model, identifying areas of potential improvement in the waste management system, or pinpointing differences between alternative scenarios.

Interpretation is further assisted by the features providing sensitivity analysis and sensitivity ratios. In the sensitivity analysis, a selected key parameter (a process, a stage, or an individual emission) is reduced by a fraction (e.g., 20%) and the consequences for the environmental impact scores immediately displayed next to the results of the original scenario. Alternatively, the sensitivity ratio automatically calculates how strongly the results are affected by a fixed change across all key parameters. This sensitivity ratio applies to any size of fixed change since the modeled impacts are

Fig. 10 Contributions of the substances in the landfill waste stream to stored ecotoxicities in soil- and water-normalized environmental impact potential scores



linear with all parameters contributing. Equation 1 is used to calculate the sensitivity ratio.

$$\text{Sensitivity\_Ratio(SR)} = \frac{\frac{\Delta\text{Output\_Variable\_i}}{\text{Output\_Varibale\_i}}}{\frac{\Delta\text{Input\_Variable\_m}}{\text{Input\_Variable\_m}}} \qquad (1)$$

The technologies examined above (conventional mineral landfill (A) and use-on-land) are analyzed to check the sensitivity to uncertainties in their data and reveal their influence on the overall results. A 20% reduction is imposed on all environmental exchanges from these technologies, and the results of the sensitivity analysis are shown in Fig. 12. The sensitivity to the change is highest for the impact categories stored ecotoxicity, water and human toxicity via soil. As seen in Figs. 8 and 10, iron (5,898 PE) resource to human toxicity via soil and copper resource to stored ecotoxicity, water are the most significant contributors, and they can be tracked further, and improvements can be optimized by facilitating different ecotechnology and recycling options.

4.6 Material balance

The EASEWASTE model provides possibilities to analyze and check the amount of each waste fraction passing through different treatment modules in a scenario. The material balance (inputs and outputs of waste material fractions to and from each module) provides the user with the possibility to view the amount of each of the defined waste sorting fractions that passes through any waste treatment module. The amount of primary waste to each technology in a treatment route for a sorting fraction is illustrated in Fig. 13.

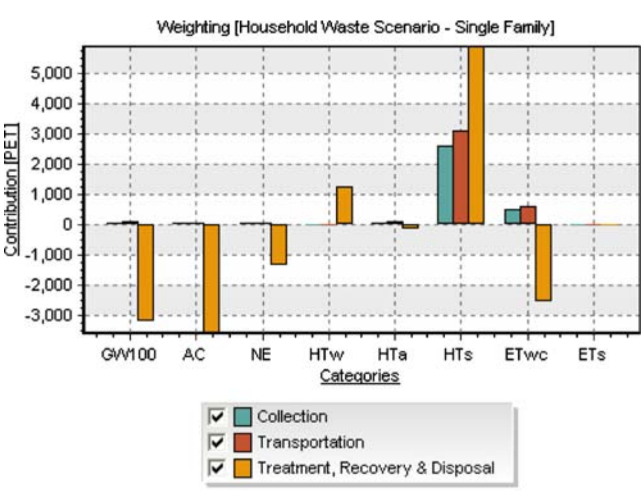


Fig. 11 Weighted results of the three modeled stages and their distribution on the individual environmental impact categories

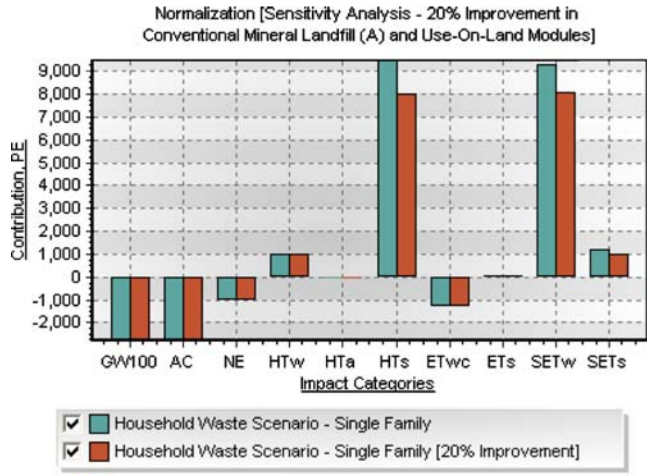
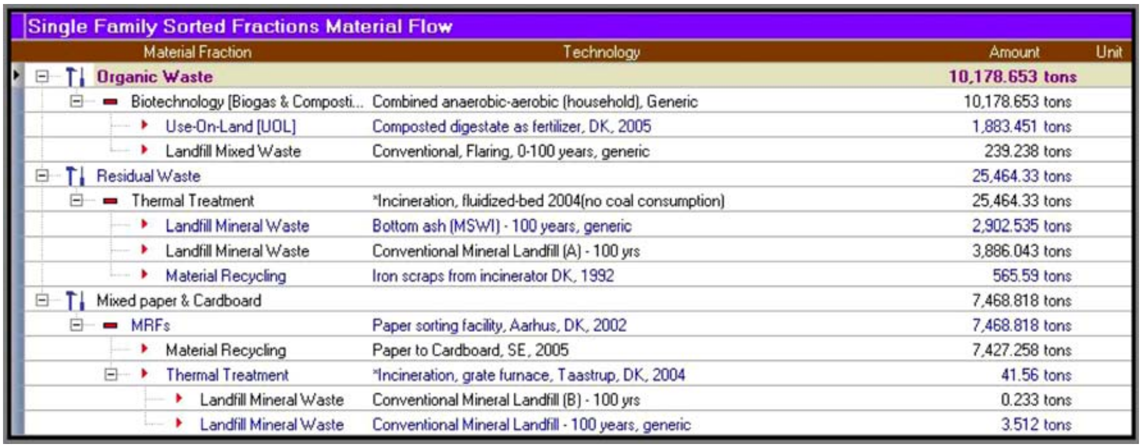


Fig. 12 Sensitivity analysis on normalized results (all environmental exchanges from conventional mineral landfill and use-on-land modules are reduced by 20% to reveal sensitivity to these modules)

5 Discussion

In order to reduce the environmental impacts from solid waste management systems, changes must be introduced to improve resource recovery and energy utilization and to limit emissions to the environment. Attention should be focused where impacts are the most severe and/or where improvement potentials are the largest and most easily obtained. This requires a systematic assessment of the whole system as provided by an LCA-based decision support model. The EASEWASTE model provides full user flexibility to the waste planner to introduce any change in a scenario at any level and to check material flow and chemical composition for each material fraction through each module (inputs and outputs to the module). Any stage (collection, transportation and treatment, recovery, and disposal) or treatment technology or sorting fraction or external process can be evaluated individually. Two or more model alternatives including scenarios, technologies, or external processes can be compared. The EASEWASTE model fully supports LCA performed according to the International Standard Organization (ISO) 14044 standard. EASEWASTE has been developed from a Scandinavian perspective, and when it is implemented in other regions, the need may arise for creation of technology modules that are not known or applied in the Scandinavian context. Likewise, some of the parameter settings may need to be changed to reflect differences in the environmental conditions (e.g., water infiltrating into landfills).

The flexibility of the waste input, waste collection method, and all treatment and disposal options means that modifications are easily done by the user. At the same time the model suggests realistic (in a Danish context) default values for most choices, which caters the model for a broad



Single Family Sorted Fractions Material Flow

Material Fraction	Technology	Amount	Unit
Organic Waste		10,178.653 tons	
Biotechnology [Biogas & Composti...	Combined anaerobic-aerobic (household), Generic	10,178.653 tons	
Use-On-Land [UOL]	Composted digestate as fertilizer, DK, 2005	1,883.451 tons	
Landfill Mixed Waste	Conventional, Flaring, 0-100 years, generic	239.238 tons	
Residual Waste		25,464.33 tons	
Thermal Treatment	"Incineration, fluidized-bed 2004(no coal consumption)	25,464.33 tons	
Landfill Mineral Waste	Bottom ash (MSWI) - 100 years, generic	2,902.535 tons	
Landfill Mineral Waste	Conventional Mineral Landfill (A) - 100 yrs	3,886.043 tons	
Material Recycling	Iron scraps from incinerator DK, 1992	565.59 tons	
Mixed paper & Cardboard		7,468.818 tons	
MRFs	Paper sorting facility, Aarhus, DK, 2002	7,468.818 tons	
Material Recycling	Paper to Cardboard, SE, 2005	7,427.258 tons	
Thermal Treatment	"Incineration, grate furnace, Taastrup, DK, 2004	41.56 tons	
Landfill Mineral Waste	Conventional Mineral Landfill (B) - 100 yrs	0.233 tons	
Landfill Mineral Waste	Conventional Mineral Landfill - 100 years, generic	3.512 tons	

Fig. 13 Waste amount of different waste fractions through different treatment modules

target audience including research staff, waste planners, and legislative consultants.

In the modeling, the treatment, recovery, and disposal options have been chosen to be either process-specific, waste-specific, or a combination, reflecting the extent to which the emissions are determined by the operation of the process or by the waste input composition. This is a choice that cannot be changed by the user and hence may limit the validity of the model if new knowledge changes the perception from the choice of EASEWASTE.

A sensitivity analysis is an indispensable part of the interpretation phase. The sensitivity analysis identifies the key figures of the LCA—those model assumptions, processes, and environmental exchanges that have the greatest bearing on the study result. Sensitivity analysis should be performed by the user to secure the validity of the assessment—any important factors can easily be identified by varying model input parameters. All important input parameters identified by the sensitivity analysis must be checked to certify that input data are correct.

LCA does not cover all dimensions that must be addressed in the waste management systems. Since LCA models do not consider concentrations in the environment caused by emissions nor assess actual exposure to emissions, LCA cannot assess actual damages to human health or ecosystems caused by the system. It also does not assess the economical performance of the system. The usefulness of LCA in waste management lies in assessing environmental efficiency. Given that all the individual operations, such as biotreatment, thermal treatment, land filling, etc. are safe and economically feasible, LCA helps determine the optimal integrated combination of these options that minimizes energy and raw material consumption and the generation of emissions to air, water, and soil.

While the EASEWASTE model can help evaluating the environmental impacts arising from a solid waste management system, other concerns must also be addressed when choosing the proper treatment routes and technologies. Costs are one of the most important factors which plays a decisive role but also issues like odor, hygiene, and social acceptability for waste generators as well as for waste collectors and workers must be taken seriously. Occupational health impacts for the latter stakeholders are also not considered in the current version of EASEWASTE. The treatment options can be modified with user-defined emissions to air, water, soil, and solid waste, but the number and routing of the produced solid residues are limited by the structure of each module. New complex waste technologies may not easily be included in the model if they do not fit into the structure of any already made module.

The EASEWASTE model has a very holistic approach to assessment of the impacts and attempts to cover all relevant resource and environmental impacts, the user must keep in mind that the model is a decision *support* tool, not a decision-*making* tool.

6 Conclusions and perspectives

The flexibility and detailed modeling level of EASEWASTE has been demonstrated with its differentiation of many individual fractions, but it has also been shown that it requires an engineering background to use all the features. The model is specially developed for the modeling of the handling of municipal solid wastes, and therefore, it does not support other wastes such as demolition and commercial waste. The model is useful for an iterative approach to waste system modeling. Its database access supports a quick primary calculation of the overall impact value for a designed waste system using default data, and based on this, the assessment can be gradually refined focusing on the parts which contribute the most to the total impacts. The EASEWASTE model allows the user to supply detailed

data for waste generation, waste composition including material fractions and chemical properties, sorting efficiencies, waste collection, and waste treatment technologies. Existing LCA tools oriented toward product modeling do not support these steps of the modeling to the same extent. The creation and evaluation of waste collection, waste transportation, and waste treatment technology individually or in a designed scenario are much easier in EASEWASTE.

EASEWASTE has been used in the modeling of a number of real case studies (e.g., Kirkeby 2004; Hansen 2005; Niskanen et al. 2009), and much data have been incorporated into it. Several research projects are currently underway under the Danish 3R (Residual Resources Recovery) research school in support of its further development (www.3r.er.dtu.dk). There are, however, still many issues that have to be improved significantly to facilitate application by other users than model developers. The improvements in consideration are to provide data for more treatment and disposal technologies and to give the user more flexibility in modeling. The current version of the model supports the environmental assessment (environmental impacts and resource consumption) of household waste treatment systems in a Danish context, but it is the ambition that future versions of the model shall support the inclusion of other waste types as well as economic evaluation (direct costs as well as external costs) and that the geographical coverage shall be extended to other countries.

More information about EASEWASTE model is available online www.easewaste.dk. Other information of the EASEWASTE model can be requested from Professor Thomas H. Christensen, Environmental Engineering Department, Technical University of Denmark (DTU), Denmark, email: thc@env.dtu.dk.

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